India needs a better gully erosion map

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Gully erosion affects India widely. Badlands, the most extreme form of land degradation caused by gullying, are also observed across large parts of Central and Western India. Akin to other environmental issues, accurate maps are critical in planning and implementing land management measures to address gully erosion. While country-wide gully erosion maps are rare commodities, India is probably the only country having several datasets including such maps. Gullies and badlands have been mapped as part of nationwide geomorphological, land degradation and wastelands mapping endeavours. However, upon examination of said maps using high-resolution imagery on Google Earth, it was found that they are largely imprecise, with each having false positive rates (gully erosion mapped where it is not present) of greater than 70%. It is suspected that the coarse spatial resolution of the satellite images used (LISS-III 23.5 m) is the root cause of such low accuracy, but feature misinterpretation by the analysts might also have contributed to it. As such, there is little to no reliable information on the magnitude of the gully erosion problem in India. Therefore, a bespoke high-resolution gully erosion map is of the essence in India's drive to realize land degradation neutrality by 2030.

Keywords: Badlands, gully erosion, gully systems, land degradation.

GULLY erosion is a geomorphic process that causes severe land degradation worldwide. It refers to the mechanism whereby concentrated (surface and/or subsurface) runoff, possibly with some shallow mass movements, erodes the soil and creates channels therein[1]. It stands out from other types of soil erosion by virtue of its deep erosive nature[2], unlike splash (or interrill) erosion, which affects the first few millimetres, and rill erosion, which maximally erodes about half a metre of the topsoil. Gully erosion rates far exceed those of surface erosion, which are already well above soil formation rates[2]. The most obvious effects of gully erosion are reduced crop yields and deterioration of inland water quality and ecology. However, sometimes it becomes especially hazardous and threatens human lives and livelihood[3,4].

Although gully systems are observed across the length and breadth of India, the badlands alongside rivers Yamuna, Chambal, Sabarmati, Mahi, Tapi, Narmada and their tributaries in Central and Western India highlight particularly intense gully erosion in these regions[5]. In 1961, the Planning Commission published the first figures on the areal extent of gully erosion in India: 41,900 km^2 (ref. 6). The National Commission of Agriculture reported a gullied area of ca. 36,700 km^2 in 1976 (ref. 7). However, these figures drew suspicion as the calculations were based on broad observations, rather than mapping or field surveys[8]. The only spatialized accounts of gully erosion in India from the previous century were provided by Ahmad[6] and Sharma[9], though only in the form of a small-scale map and broad zonation respectively (Figure 1).

Precise spatial information is crucial in the management and remediation of any environmental concern. Even though gully erosion is certainly the most destructive kind of soil erosion, it can easily be identified and mapped from remotely sensed imagery of an appropriately high spatial resolution. However, thorough areal or polygonal gully mapping for an entire country is bound to be quite laborious and time-consuming, unless the country is small, such as South Africa[10]. It is, therefore, quite a surprise that a country as big as India has multiple datasets including an areal map of gully erosion, viz. land degradation[11], wastelands[12] and geomorphological atlases[13]. However, the respective mapping reports quote dissimilar figures of the total land area affected by gully erosion in India: 24,613 km^2 (geomorphological atlas), 25,406 km^2 (land degradation atlas) and 9,953 km^2 (wastelands atlas). While

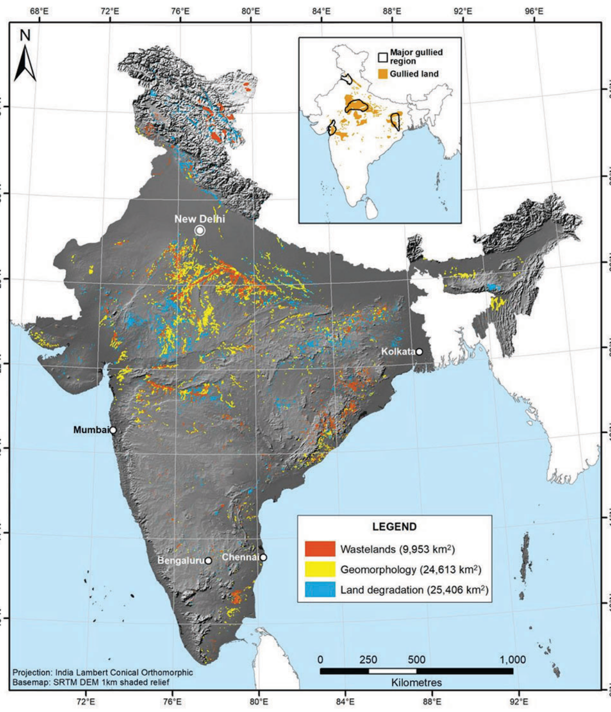

Figure 1. Variable spatial extents of gully erosion in India as obtained from the latest land degradation, geomorphological and wastelands atlases. Inset map shows the gullied lands map (1 : 15 million) of Ahmad[6] and regions facing severe gully erosion as delineated by Sharma[9].

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Table 1. Categorical false positive rates of the existing gully maps

Dataset	Category	Number of features assessed	Correctly mapped features	False positive rate (%)
Land degradation	Gullies	100	12	88
	Shallow ravines	100	32	68
	Deep ravines	100	37	63
Geomorphology	Gullied tract	100	17	83
	Gullied land	100	20	80
	Badland	100	15	85
Wastelands	Gullied and/or ravinous land	100	14	86

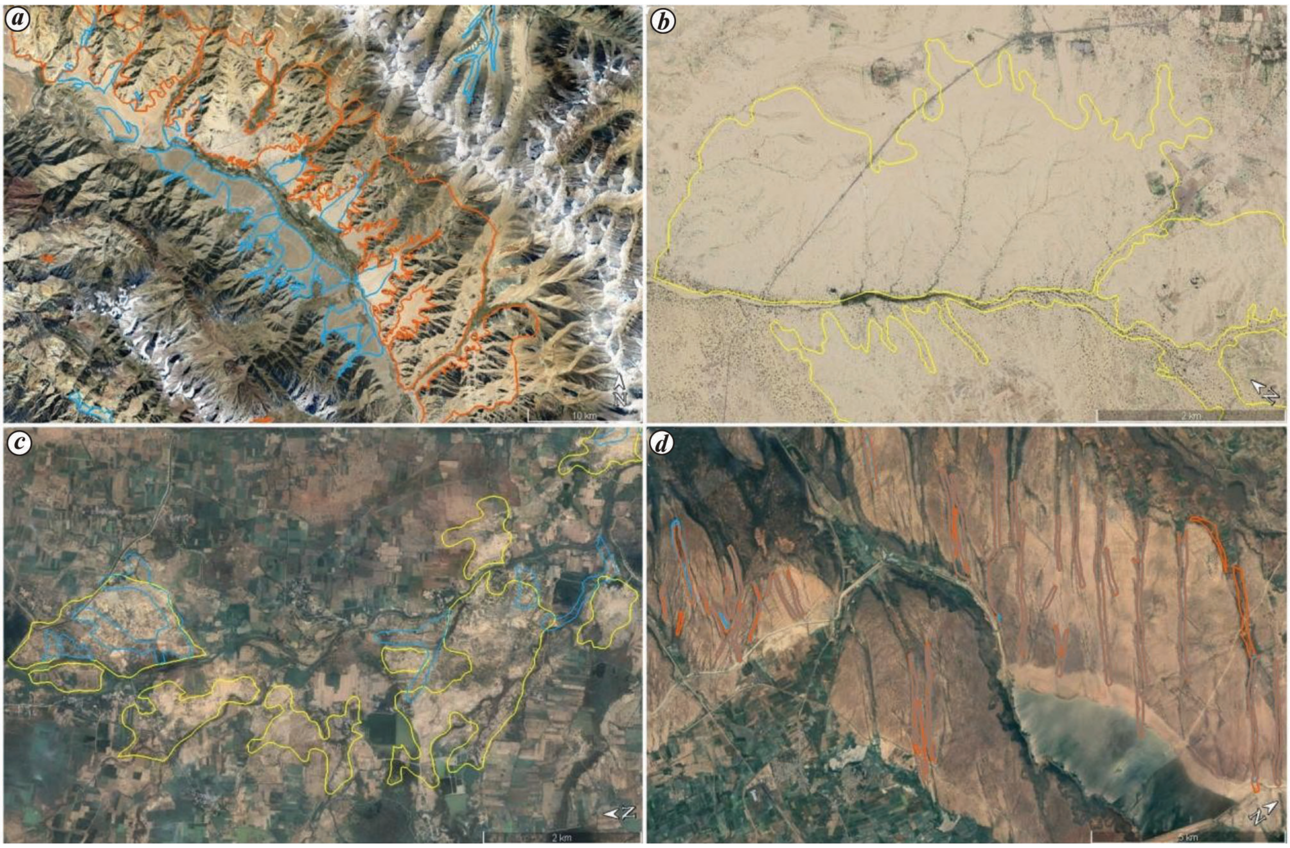

Figure 2. (***a***) Bedrock incisions and alluvial fans, (***b***) first-order channels, (***c***) scrub and (***d***) rock fractures/joints mapped as gullies by the wastelands (in red), geomorphological (in yellow) and land degradation (in blue) atlases.

the gullied area figures reported in the geomorphological and land degradation atlases are comparable, the respective maps depicting the distribution of gullied lands are not (Figure 1). As all three datasets were produced at the same scale of 1 : 50,000, solely through visual interpretation of the same satellite imagery (IRS LISS-III multispectral 23.5 m), presence of such contrasts between the gully maps served as a motivation for undertaking this work.

The geomorphological atlas was downloaded from the Bhukosh data portal (https://bhukosh.gsi.gov.in/Bhukosh/Public) of the Geological Survey of India, while the other two were loaded in QGIS from the Bhuvan Geo-portal (https://bhuvan.nrsc.gov.in/) as WMS layers and subsequently saved as GeoTIFF files, following which the pertinent map categories were extracted for this analysis. The geomorphological atlas has three classes of interest, namely, *Badland*, *Gullied Land* and *Gullied Tract*. Relevant groups from the land degradation dataset are *Gullies*, *Shallow Ravines* and *Deep Ravines*, while the wastelands map only has one such category, i.e. *Gullied* and/or *Ravinous Land*. It must be noted that the term 'ravines' is used in India simply as a synonym for 'badlands'[5].

Categorical accuracies of the existing gully maps have been quantified. The key requirement in the accuracy assessment of maps derived from remotely sensed images is that the reference data is randomly collected and is atleast one level more accurate (has a higher resolution) than the map to be assessed[14]. Therefore, 100 randomly selected mapped features from each gully erosion class of the three datasets have been evaluated vis-à-vis high-resolution imagery on Google Earth, checking whether a mapped feature correctly represents gully erosion therein (i.e. true positives).

The wastelands map was found to have the highest false positive rate or commission error (86%), closely followed by that of the geomorphological map (82.67%), while the land degradation map has an appreciably lower false positive rate of 73%. The categorical accuracies of the geomorphology map are largely similar, but the two classes of *Shallow Ravines* and *Deep Ravines* from the land degradation dataset have appreciably lesser false positive rates than the *Gullies* class (Table 1). In sum, of the 700 features assessed, a paltry 21% were found to have been mapped accurately.

It can reasonably be concluded from the above that India's existing gully maps are largely inaccurate. Their poor accuracies undoubtedly stem from the rather coarse resolution of the source imagery (LISS-III 23.5 m) relative to the dimensions of the features in question, especially gullies. The *Shallow Ravines* and *Deep Ravines* categories from the land degradation atlas were found to be considerably more precise, thus hinting at the fact that the image resolution of 23.5 m is probably appropriate in delineating badlands when they can be spectrally and spatially differentiated. Nevertheless, the comparable categories from the geomorphology dataset, i.e. *Badlands* and *Gullied Tract*, were surprisingly its least accurate classes. However, as all three atlases were prepared solely through visual assessment, the chances of misinterpretation on the part of the analysts cannot be ruled out. It has been noticed that geomorphic features as disparate as gorges/canyons, first-order (ephemeral) channels and even joints or fractures were mistakenly mapped as gully erosion features in one or more of these datasets (Figure 2). On the contrary, it is likely that many areas undergoing gully erosion have not been detected by one or more of these atlases (false negatives), which could not be quantified. Nonetheless, the figures of gullied area as reported by these atlases, cannot be relied upon. As was noticed during this evaluation, many polygons demarcating badlands extend far beyond their current extents, likely due to progressive reclamation[15], which is not reflected in the existing maps (Figure 3), hence overestimating the affected area manifold.

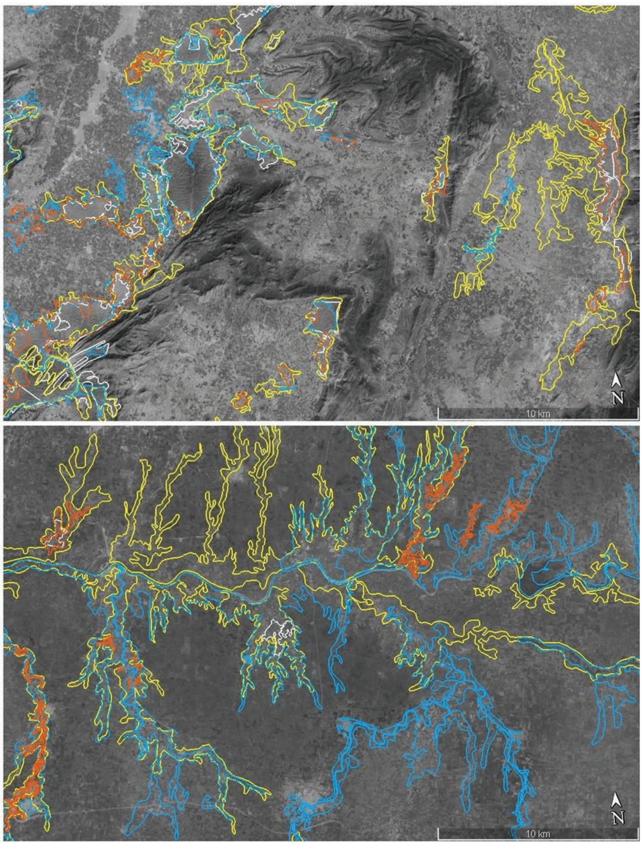

Figure 3. Polygons demarcating badlands from the wastelands (in red), geomorphological (in yellow) and land degradation (in blue) atlases, compared against current badlands' extents (in white) in Rajasthan (top) and Maharashtra (bottom), delineated on Google Earth.

As India strives to attain land degradation neutrality by 2030 (ref. 16), combating gully erosion and effectively managing the badlands will be of great importance. Therefore, having precise data on the spatial extents of gullies and badlands is vital. However, none of the existing datasets are accurate enough to be used further as standalone gully occurrence maps, let alone as tools to inform land management. A bespoke high-resolution gully erosion map, created possibly using Google Earth imagery and/or recently released open-source IRS-LISS IV 5.8 m multispectral data, is necessary.

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